

Inconsistencies in Interacting Agegraphic Dark Energy Models

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Abstract

It is found that the origin agegraphic dark energy tracks the matter in the matter-dominated epoch and then the subsequent dark-energy-dominated epoch becomes impossible. It is argued that the difficulty can be removed when the interaction between the agegraphic dark energy and dark matter is considered. In the note, by discussing three different interacting models, we find that the difficulty still stands even in the interacting models. Furthermore, we find that in the interacting models, there exists the other serious inconsistency that the existence of the radiation/matter-dominated epoch contradicts the ability of agegraphic dark energy in driving the accelerated expansion. The contradiction can be avoided in one of the three models if some constraints on the parameters hold.

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1 Introduction

Increasing evidence suggests that the expansion of our universe is being accelerated [1, 2, 3]. Within the framework of the general relativity, the acceleration can be phenomenally attributed to the existence of a mysterious exotic component with negative pressure, namely the dark energy [4, 5]. However, we know little about the nature of dark energy. The most nature, simple and

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important candidate for dark energy is the Einstein's cosmological constant, which can fit the observations well so far. But the cosmological constant is plagued with the well-known fine-tuning and cosmic coincidence problems [4, 5]. Dark energy has become one of the most active fields in the modern cosmology.

Recently, the so-called agegraphic dark energy model is suggested [6]. The energy density of agegraphic dark energy is given by [6]

$$\rho_D = \frac{3n^2 M_p^2}{T^2}. \quad (1)$$

Here $M_p = (8\pi G)^{-1/2}$ and T is chosen to be the age of our universe

$$T = \int_0^t dt' = \int_0^a \frac{da}{Ha}, \quad (2)$$

where a is the scale factor of our universe, $H \equiv \dot{a}/a$ is the Hubble parameter and a dot denotes the derivative with respect to cosmic time. However, it is found that the agegraphic dark energy proposed in [6] tracks the matter in the matter-dominated epoch [7]. This can be understood easily [9]. In the matter-dominated epoch, $a \propto t^{2/3}$. Then we have $\rho_D \propto a^{-3}$. Since the energy density of matter $\rho_m \propto a^{-3}$, ρ_D tracks ρ_m in the matter-dominated epoch and the dark-energy-dominated epoch becomes impossible. This is of course unacceptable.

Two ways out of the difficulty are suggested. The first one is to replace T with $T + \delta$ [6], where δ is a constant with dimension of time. The second one is the so-called new agegraphic dark energy by replacing T with the conformal time η [7]. Both of the ways change Eq.(1). In [10], it is argued that the difficulty in the origin version can also be removed when the interaction between the agegraphic dark energy and matter is considered.

In note, the interacting agegraphic dark energy models with three different forms of interaction are considered respectively. We find that in the model with interaction proportional to the energy density of matter, ρ_D still tracks ρ_m in the matter-dominated epoch. Furthermore, we find that the existence of the matter-dominated epoch contradicts the ability of agegraphic dark energy in driving the accelerated expansion even in the interacting models.

The paper is organized as follows. In the next section, we will discuss the difficulties of the agegraphic dark energy. In Sec.3, we will recall the analysis in [10] which tells us that the agegraphic dark energy will not track the matter during the matter-dominated epoch if the interaction between agegraphic dark energy and dark matter is considered. In Sec.4, we will show that there exists the other inconsistence in the interacting models. Finally, Conclusions and Discussions are given.

2 Inconsistencies in Agegraphic Dark Energy Model

Considering the flat Friedmann-Robertson-Walk universe with the agegraphic dark energy and pressureless matter, the corresponding Friedmann equation is

$$H^2 = \frac{1}{3M_p^2}(\rho_m + \rho_D). \quad (3)$$

By defining

$$\rho_c = 3H^2M_p^2, \quad \Omega_m = \frac{\rho_m}{\rho_c}, \quad \Omega_D = \frac{\rho_D}{\rho_c}, \quad (4)$$

we may rewrite the Friedmann equation as

$$1 = \Omega_m + \Omega_D. \quad (5)$$

And from Eq.(1), we can easily find that

$$\Omega_D = \frac{n^2}{H^2T^2}. \quad (6)$$

The conservation laws of the agegraphic dark energy and matter are respectively

$$\dot{\rho}_m + 3H\rho_m = 0, \quad (7)$$

$$\dot{\rho}_D + 3H(1+w_D)\rho_D = 0, \quad (8)$$

where w_D is the equation-of-state (EoS) parameter of the agegraphic dark energy. Taking the derivative of Eq.(1) with respect to the cosmic time t , we can get

$$\dot{\rho}_D + H\frac{2\sqrt{\Omega_D}}{n}\rho_D = 0. \quad (9)$$

Comparing the equation with Eq(8), we get [6]

$$w_D = -1 + \frac{2}{3n}\sqrt{\Omega_D}. \quad (10)$$

From Eq.(6) and using Eqs.(3), (4), (7) and (9), we can have [6]

$$\Omega'_D = \Omega_D(1-\Omega_D)\left(3 - \frac{2}{n}\sqrt{\Omega_D}\right), \quad (11)$$

where a prime denotes the derivative with respect to the e-folding time $N = \ln a$. The evolution of Ω_D governed by Eq.(11) has been analyzed in Ref.[6] and it is found that the agegraphic dark energy model works well [6].

However, it is found in [6, 7] that there exists an implicit inconsistence in the agegraphic dark energy model. In the matter-dominated epoch with $\Omega_D \ll 1$, the Friedmann equation approximately becomes

$$H^2 \simeq \frac{1}{3M_p^2} \rho_m. \quad (12)$$

Together with Eq.(7), we have $a \propto t^{2/3}$. Then we have

$$H = \frac{2}{3t}.$$

Substituting the result into Eq.(6), we have

$$\Omega_{DI} = \frac{9n^2}{4}. \quad (13)$$

Hereafter we use the subscript I to denote the initial value of Ω_D when deep in the matter-dominated epoch. It can be easily checked that Eq.(13) is also a critical point of Eq.(11). In fact, there exist the other two critical points of Eq.(11),

$$\Omega_{D1} = 0, \quad (14)$$

$$\Omega_{D2} = 1. \quad (15)$$

Obviously, Eq.(14) is unstable. Since Eq.(13) is the value of Ω_D deep in the matter-dominated epoch, then we have

$$\Omega_{DI} = \frac{9n^2}{4} \ll 1. \quad (16)$$

With this result, it can be checked easily that Eq.(13) is an attractor, while Eq.(15) is unstable. This implies $\Omega_D \rightarrow \frac{9n^2}{4} \ll 1$ as $\ln a \rightarrow +\infty$ and the subsequent dark-energy-dominated epoch becomes impossible.

Furthermore, we find that Eq.(13) indicates the other serious problem. This can be easily shown as follows. From Eq.(16), we have

$$n \ll 1.$$

On the other hand, Eq.(10) tells us that the necessary condition for agegraphic dark energy to drive the accelerated expansion is

$$n > 1. \quad (17)$$

So the matter-dominated epoch contradicts the ability of agegraphic dark energy in driving the accelerated expansion.

A similar conclusion is also given in Ref.[8]. By extending the discussion of agegraphic dark energy model to include the radiation-dominated epoch, the author in [8] noted that the bound imposed on the fractional dark energy density parameter $\Omega_D < 0.1$ during the big bang nucleosynthesis (BBN) requires

$$n < \frac{1}{6}. \quad (18)$$

The contradiction between Eqs(17) and (18) is obvious. Then it is interesting for us to explore whether the contradiction can be solved when the interaction is involved.

3 Interacting Agegraphic Dark Energy Models

In [10], it is shown that the agegraphic dark energy will not track the matter when the interaction between the agegraphic dark energy and matter is considered. In the section, we will recall the analysis in [10]. In the next section, we will show that, actually, there still exist some inconsistencies even in the interacting models.

The conservation laws of the agegraphic dark energy and matter are respectively [10]

$$\dot{\rho}_m + 3H\rho_m = Q, \quad (19)$$

$$\dot{\rho}_D + 3H(1+w_D)\rho_D = -Q, \quad (20)$$

where Q denotes the phenomenological interaction term. Comparing Eq.(9) and Eq.(20), we have [10]

$$w_D = -1 + \frac{2}{3n}\sqrt{\Omega_D} - \frac{Q}{3H\rho_D}. \quad (21)$$

If $Q = 0$, the equation reduces to Eq.(10). From Eqs.(3), (9) and (19), we have

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho_m - 2\rho_D + \frac{2\sqrt{\Omega_D}}{n}\rho_D - \frac{Q}{H}\right). \quad (22)$$

From Eq.(6) and using Eqs.(3), (4), (9) and (19), we can obtain the evolving equation of Ω_D with interaction [6]

$$\Omega'_D = \Omega_D \left[(1 - \Omega_D) \left(3 - \frac{2}{n}\sqrt{\Omega_D} \right) - \frac{Q}{3M_p^2 H^3} \right]. \quad (23)$$

If $Q = 0$, this equation reduces to Eq.(11).

In [10], Eq.(23) has been solved numerically with the initial condition $\Omega_{D0} = 0.7$, and the reasonable evolution of Ω_D has been shown that the agegraphic dark energy is negligible in the past and eventually dominates the evolution of our universe. Then it seems to be reasonable to conclude that the inconsistency in the non-interacting agegraphic dark energy has been removed in the interacting models. However, as shown below, we find that there still exist the inconsistencies in the interacting agegraphic dark energy models.

4 Inconsistencies in Interacting Agegraphic Dark Energy Models

In the section, owing to the lack of the knowledge of micro-origin of the interaction, we simply consider three forms of the interaction

$$Q = 3\beta H\rho_m, \quad 3\alpha H\rho_D, \quad 3\gamma H(\rho_m + \rho_D), \quad (24)$$

which are used in the literature most often [10, 11, 12, 13, 14, 15]. Here β, α and γ are positive constants.

4.1 $Q = 3\beta H\rho_m$

Firstly, we consider the interacting agegraphic dark energy model with $Q = 3\beta H\rho_m$. Then Eq.(23) reads

$$\Omega'_D = \Omega_D(1 - \Omega_D) \left[3(1 - \beta) - \frac{2}{n} \sqrt{\Omega_D} \right]. \quad (25)$$

And the conservation law of matter reads

$$\dot{\rho}_m + 3H\rho_m = 3H\beta\rho_m. \quad (26)$$

From the above equation, we can easily obtain

$$\rho_m \propto a^{-3(1-\beta)}. \quad (27)$$

Then, in the matter-dominated epoch with $\Omega_D \ll 1$, from Eq.(12), we have

$$a \propto t^{\frac{2}{3(1-\beta)}} \Rightarrow H = \frac{2}{3(1-\beta)} \frac{1}{t}. \quad (28)$$

Substituting the equation into Eq.(6), we have

$$\Omega_{DI} = \left[\frac{3(1-\beta)n}{2} \right]^2. \quad (29)$$

This is the initial value of Ω_D in the model with $Q = 3\beta H\rho_m$ when deep in the matter-dominated epoch. It can be checked easily that Eq.(29) is also a critical point of Eq.(25). And the other two critical points of Eq.(25) are given in Eqs.(14) and (15) respectively. Since deep in the matter-dominated epoch

$$\Omega_{DI} \ll 1, \quad (30)$$

then we can find that Eq.(29) is an attractor of Eq.(25) while the other two critical points of Eq.(25) are unstable. This implies $\Omega_D \rightarrow \left[\frac{3(1-\beta)n}{2}\right]^2 \ll 1$ as $\ln a \rightarrow +\infty$ and the subsequent dark-energy-dominated epoch becomes impossible.

Furthermore, we find that the contradiction between the matter-dominated epoch and the ability of agegraphic dark energy in driving the accelerated expansion also exists in the interacting model. Let us show it. From Eq.(22), in the matter-dominated epoch, approximately we have

$$\frac{\ddot{a}}{a} \simeq -\frac{4\pi G}{3}(1-3\beta)\rho_m,$$

since $\rho_D \ll \rho_m$. Then we must have

$$\beta < \frac{1}{3}, \quad (31)$$

since, if $\beta > \frac{1}{3}$, the expansion of the universe during the matter-dominated epoch would be accelerated and then the observed large scale structure of the universe could not be formed. Substituting $\beta < \frac{1}{3}$ into Eq.(29), we have

$$\Omega_{DI} > n^2. \quad (32)$$

Then together with Eq.(30), we have

$$n \ll 1, \quad (33)$$

On the other hand, in the dark-energy-dominated epoch, since $\Omega_D \simeq 1$ and $\rho_m \ll \rho_D$, from Eq.(22) we have

$$\frac{\ddot{a}}{a} \simeq -\frac{8\pi G}{3}\left(\frac{1}{n}-1\right)\rho_D, \quad (34)$$

where $Q = 3\beta H\rho_m$ has been used. Then in order for the agegraphic dark energy to drive the accelerated expansion, we must have

$$n > 1.$$

Obviously, this result contradicts Eq.(33). So the contradiction between the matter-dominated epoch and the ability of agegraphic dark energy in driving the accelerated expansion still stands in the interacting model with $Q = 3\beta H\rho_m$.

4.2 $Q = 3\alpha H\rho_D$

Secondly, we consider the case of $Q = 3\alpha H\rho_D$. Then Eq.(23) reads

$$\Omega'_D = \Omega_D \left[(1-\Omega_D) \left(3 - \frac{2}{n} \sqrt{\Omega_D} \right) - 3\alpha\Omega_D \right]. \quad (35)$$

In the matter-dominated epoch, Eq.(19) reads approximately

$$\dot{\rho}_m + 3H\rho_m \simeq 0, \quad (36)$$

since $\rho_D \ll \rho_m$. Then in the matter-dominated epoch, approximately we have

$$\rho_m \propto a^{-3}, \quad (37)$$

So from Eqs.(12) and (37), we have

$$a \propto t^{\frac{2}{3}} \Rightarrow H = \frac{2}{3t}. \quad (38)$$

Substituting the equation into Eq.(6), we have

$$\Omega_{DI} = \frac{9n^2}{4}. \quad (39)$$

Then, when deep in the matter-dominated epoch, we have the same initial value of Ω_D as in the non-interacting model. But the case is different. Here, due to the interaction, Eq.(39) is not the critical point of the evolving equation (35). Then it seems that the tracking behavior of agegraphic dark energy during the matter-dominated epoch is eliminated, and eventually the agegraphic dark energy will become dominated. However, we find this problem still stands. As in the non-interacting model, here we also have

$$\Omega_{DI} = \frac{9n^2}{4} \ll 1. \quad (40)$$

Then, using this result, from Eq.(35), we find

$$\Omega'_D < 0, \quad \text{for } \Omega_{DI} \leq \Omega_D \leq 1. \quad (41)$$

Here we have used $\alpha > 0$. Eq.(41) tells us that Ω_D will never become larger than $\frac{9n^2}{4}$ and will approach a value less than $\Omega_{DI} = \frac{9n^2}{4}$ as $\ln a \rightarrow +\infty$, and consequently the subsequent dark-energy-dominated epoch is impossible.

Now let us show whether the contradiction between the matter-dominated epoch and the ability of agegraphic dark energy in driving the accelerated expansion exists in the case. Eq.(40) implies

$$n \ll 1. \quad (42)$$

On the other hand, in the dark-energy-dominated epoch, since $\Omega_D \simeq 1$ and $\rho_D \gg \rho_m$, from Eq.(22), approximately we have

$$\frac{\ddot{a}}{a} \simeq -\frac{4\pi G}{3} \left(-2 + \frac{2}{n} - 3\alpha \right) \rho_D.$$

Then, in order for the agegraphic dark energy to drive the accelerated expansion, we must have

$$\frac{1}{n} < 1 + \frac{3}{2}\alpha. \quad (43)$$

Together with Eq.(43), we have

$$\frac{2}{2 + 3\alpha} < n \ll 1. \quad (44)$$

Then in the interacting model, we can remove the contradiction between the matter-dominated epoch and the ability of agegraphic dark energy in driving the accelerated expansion if Eq.(44) holds.

4.3 $Q = 3\gamma H(\rho_D + \rho_m)$

Finally, we consider the case of $Q = 3\gamma H(\rho_D + \rho_m)$. In the case Eq.(23) reads

$$\Omega'_D = \Omega_D \left[(1 - \Omega_D) \left(3 - \frac{2}{n} \sqrt{\Omega_D} \right) - 3\gamma \right]. \quad (45)$$

In the matter-dominated epoch, since $\rho_D \ll \rho_m$, the conservation law of matter reads approximately

$$\dot{\rho}_m + 3H(1 - \gamma)\rho_m \simeq 0. \quad (46)$$

Then we have

$$\rho_m \propto a^{-3(1-\gamma)}. \quad (47)$$

Together with Eq.(12), in the matter-dominated epoch we have

$$a \propto t^{\frac{2}{3(1-\gamma)}} \Rightarrow H = \frac{2}{3(1-\gamma)} \frac{1}{t}. \quad (48)$$

Substituting the equation into Eq.(6), we have

$$\Omega_{DI} = \left[\frac{3(1-\gamma)n}{2} \right]^2. \quad (49)$$

Due to the interaction, Eq.(49) is not the critical point of Eq.(45). However, since in the matter-dominated epoch

$$\Omega_{DI} = \left[\frac{3(1-\gamma)n}{2} \right]^2 \ll 1, \quad (50)$$

then from Eq.(45) we find

$$\Omega'_D < 0, \quad \text{for } \Omega_{DI} \leq \Omega_D \leq 1. \quad (51)$$

Here $\gamma > 0$ has been used. As in the case of $Q = 3\alpha H\rho_D$, Eq.(51) tells us that Ω_D will approach a value smaller than $\Omega_{DI} = \left[\frac{3(1-\gamma)n}{2}\right]^2$ as $\ln a \rightarrow +\infty$ and the subsequent dark-energy-dominated epoch becomes impossible.

Furthermore, we find that as in the case of $Q = 3\beta H\rho_m$, in the model with $Q = 3\gamma H(\rho_D + \rho_m)$, the matter-dominated epoch contradicts the ability of agegraphic dark energy in driving the accelerated expansion, too. Let us show it. In the matter-dominated epoch, since $\rho_D \ll \rho_m$, from Eq.(22), approximately we have

$$\frac{\ddot{a}}{a} \simeq -\frac{4\pi G}{3}(1-3\gamma)\rho_m, \quad (52)$$

Then we must have

$$\gamma < \frac{1}{3}, \quad (53)$$

in order for the expansion of the universe to be decelerated to form the large scale structure during the matter-dominated epoch. Using Eqs.(53) and (50) we have

$$n \ll 1. \quad (54)$$

On the other hand, in the dark-energy-dominated epoch, since $\rho_D \gg \rho_m$ and $\Omega_D \simeq 1$, from Eq.(22), approximately we have

$$\frac{\ddot{a}}{a} \simeq -\frac{4\pi G}{3}\left(-2 + \frac{2}{n} - 3\gamma\right)\rho_D, \quad (55)$$

where $Q = 3\gamma H(\rho_D + \rho_m) \simeq 3\gamma H\rho_D$ has been used. Then the necessary condition for agegraphic dark energy to drive the accelerated expansion is

$$n > \frac{2}{2+3\gamma}. \quad (56)$$

Together with Eq.(53), we have

$$n > \frac{2}{3}. \quad (57)$$

Roughly, it seems that Eq.(57) may not contradict Eq.(54). But the contradiction between Eq.(57) and Eq.(18) is obvious. Here we note that the condition (18) imposed by BBN on the agegraphic dark energy model is not effected by the interaction between dark energy and matter, since both agegraphic dark energy and matter are negligible during the radiation-dominated epoch. So, in the interacting agegraphic dark energy model with $Q = 3\gamma H(\rho_D + \rho_m)$, the existence of the radiation-dominated epoch contradicts the ability of agegraphic dark energy in driving the accelerated expansion.

5 Conclusions and Discussions

In this note, we recall the inconsistency in the origin agegraphic dark energy model that the agegraphic dark energy tracks the matter in the matter-dominated epoch. And furthermore, we point out that there is the other more serious inconsistency in the model that the matter-dominated epoch contradicts the ability of agegraphic dark energy in driving the accelerated expansion.

Then, by considering three kinds of phenomenological interaction between the agegraphic dark energy and matter, we analyze the interacting agegraphic dark energy models. We find that in the dark energy model with interaction $Q = 3\beta H\rho_m$, the agegraphic dark energy still tracks the matter during the matter-dominated epoch, and the contradiction between the existence of the matter-dominated epoch and the ability of the agegraphic dark energy in driving the accelerated expansion also exists. In the models with $Q = 3\alpha H\rho_D$ and $Q = 3\alpha H\rho_D$, it is still impossible for agegraphic dark energy to become dominated. And in the model with $Q = 3\alpha H\rho_D$ the contradiction between the existence of the matter-dominated epoch and the ability of the agegraphic dark energy in driving the accelerated expansion can be avoided if the condition (44) holds. But in the model with $Q = 3\gamma H(\rho_m + \rho_D)$, the ability of the agegraphic dark energy in driving the accelerated expansion contradicts the bound imposed by BBN on the agegraphic dark energy.

Then it seems that none of the three interacting agegraphic dark energy models can be taken as serious candidate for realistic dark energy. In Ref.[17], the authors studied the interacting agegraphic dark energy model by using a general form of interaction $Q = 3H(\alpha\rho_D + \beta\rho_m)$. In the matter-dominated epoch with $\rho_D \ll \rho_m$, the interaction reduces to $Q \simeq 3H\beta\rho_m$. So β and n should satisfy the constraints (31) and (33) respectively, since the two constraints are obtained by analyzing the model with $Q = 3H\beta\rho_m$ during the matter-dominated epoch. Similarly, since the general interaction form reduces to $Q \simeq 3H\alpha\rho_D$ in the dark-energy-dominated epoch, α and n should satisfy the condition (44). However, it can be checked easily that the values of parameters used in Ref.[17] does not satisfy Eq.(44). Then there exist implicit inconsistencies in the interacting agegraphic dark energy models analyzed in Ref.[17], although the authors obtained the reasonable behaviors of Ω_D and Ω_m by solving the evolving equations numerically. This would not be confusing or astonishing if we recall that even in the non-interacting agegraphic dark energy model, the reasonable behavior of Ω_D can be obtained by solving the evolving equations numerically with $n = 3$ and the initial condition $\Omega_{D0} = 0.73$.

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